

Long-lived heavy quarks : a review

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We review the theoretical and experimental situation for long-lived heavy quarks, or bound states thereof, arising in simple extensions of the Standard Model. If these particles propagate large distances before their decay, they give rise to specific signatures requiring dedicated analysis methods. In particular, vector-like quarks with negligible couplings to the three known families could have eluded the past experimental searches. While most analyses assume prompt decays at the production vertex, novel heavy quarks might lead to signatures involving displaced vertices, new hadronic bound states, or decays happening outside of the detector acceptance. We perform reinterpretations of existing searches for short- and long-lived particles, and give suggestions on how to extend their reach to long-lived heavy quarks.

I. INTRODUCTION

Over the past decades, we have discovered that Nature consists of a given number of elementary particles, deeply connected with the known fundamental forces driving our universe. The recent observation of a new particle resembling the long-sought Higgs boson at the Large Hadron Collider (LHC) now provides us with strong evidence for the validity of the Standard Model (SM) [1, 2]. Yet, while it is generally acknowledged that the latter comprises three generations of chiral quarks and leptons, various fundamental problems do not find their answers within this framework. For instance, long-standing issues such as the origin of the fermion mass hierarchy or the nature of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix hint at the possible need for new physics. While the SM is expected to lose its predictive power as the experimental searches now reach the TeV scale, models suggesting new heavy fermions might offer promising solutions to these problems in the near future.

Although a fourth sequential family of quarks is now claimed to be disfavoured by the recent results of the searches for the Higgs boson [3], other models predicting new heavy particles beyond the top quark are still consistent with the current experimental measurements. In particular, the possibility for vector-like quarks, *i.e.*, quarks having their left- and right- handed components transforming identically under the electroweak gauge group, are a common feature of many scenarios going beyond the SM. Grand unified models based on E_6 , for

example, predict the existence of isoscalar, charge $-1/3e$ quarks with small, quite possibly tiny mixing to the well-known doublet quarks [4]. Non-chiral quarks also have the peculiarity to decouple in the heavy mass limit, leading to SM-like signals. Should the mixings of these with the light SM fermions be suppressed, the Higgs production rates would not be easily distinguishable from the SM expectations [5]. These new quarks could be sufficiently long-lived to behave like effectively stable particles, evading the current searches as they propagate over sizeable distances.

From the collider searches it is clear that if new states with masses less than a hundred GeV had existed, they would have been observed. On the other hand, the experimental reach for detecting novel heavy stable particles above a few TeV depends on how readily identifiable such states are at the LHC. While long-lived particles could fly away from the primary interaction point before they decay to ordinary particles and lead to displaced vertices, they can also hadronise, allowing for a possibly rich spectrum of new exotic and heavy bound states. Such stable massive particles are also anticipated at the TeV scale in many new physics models, either due to the presence of a new conserved quantum number (*e.g.*, R parity in supersymmetry), or because the decays are suppressed by kinematics or couplings (see [6] and references therein for an exhaustive review). Although the majority of the past studies focused on stable states in supersymmetry, the possibility for new stable quarks received few attention at the LHC. While the CMS and ATLAS experiments are now setting strong limits on long-lived gluino, stop and stau pair production (see, for instance, [7] and [8]), scenarios involving quasi-stable heavy quarks have been barely investigated at the LHC.

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In the following, we review the phenomenology of new, long-lived heavy quarks. Assuming a general parametrisation, Section II first examines their production and decay modes at the LHC, considering both the chiral and vector-like scenarios. The possible signatures for displaced vertices and stable massive hadrons are then covered within the context of negligible mixings with the SM fermions. The experimental aspects of the collider searches for new long-lived quarks are presented in Section III. We review the situation for prompt decay searches, displaced vertices and Heavy Stable Charged Particles (hereafter, HSCPs) and highlight some of their limitations. Reinterpretations of the existing searches are then presented for short- and long-lived particles. Considering the possibility to improve the sensitivity of the existing analyses to long-lived quarks beyond the TeV scale, some alternative search topologies are finally described. Our conclusions are given in Section IV.

II. LONG-LIVED QUARKS SIGNATURES

A. Production

As we review the possibility for long-lived quarks in general, two different scenarios will be distinguished in this work. New chiral fermions, for which the left- and right-handed chiralities have different charges under the electroweak gauge group, gain their masses from the electroweak symmetry breaking mechanism. If heavy, a sequential fourth generation quark doublet $(t', b')_L$ can therefore induce large corrections to loop observables. Such a scenario is now severely constrained from the flavour and electroweak precision data, and from the Higgs searches results. Given that chiral fermions couple to the Higgs boson with a strength proportional to their Yukawa couplings, they do not decouple from its production, as its rate should increase by a factor of about 9 due to the additional fermion loops occurring in gluon fusion. The unobserved enhancement thus now strongly disfavors a fourth generation Standard Model [3].

Non-chiral quarks, on the other hand, still provide a viable extension to the SM and certainly require a dedicated discussion. Considering the introduction of vector-like $SU(3)_C$ colour triplets, new parameters have to be added, namely, their masses and all associated couplings. Such quantities arise naturally from the corresponding $SU(2)_L \times U(1)_Y$ invariant Yukawa interactions and Dirac mass terms in the SM Lagrangian. The light quark couplings to the Higgs and electroweak bosons are consequently modified, along with the introduction of new Yukawa and gauge couplings between the heavy and the SM quarks.

Still, it is important to emphasise that such new states cannot have arbitrary quantum numbers, since they can only mix with the SM quarks through a limited number of gauge-invariant couplings. Classifying them into $SU(2)_L$ multiplets, their Yukawa terms only allow for

Q_q	$T_{\frac{2}{3}}$	$B_{-\frac{1}{3}}$	$\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \end{pmatrix}$	$\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\begin{pmatrix} B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$	$\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$
T_3	0	0	1/2	1/2	1/2	1	1
Y	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3

TABLE I. Vector-like multiplets allowed to mix with the SM quarks through Yukawa couplings. The electric charge is the sum of the third component of isospin T_3 and of the hypercharge Y . Adapted from [9].

seven distinct possibilities, *i.e.*, the two singlets, the three doublets and the two triplets displayed in Table I.

The production of such new heavy quarks, either chiral or vector-like, is usually assumed to proceed dominantly at the LHC through gluon fusion, $gg \rightarrow Q\bar{Q}$. Nevertheless, depending on the model at hand, electroweak single production can also provide an alternative mechanism as it is not affected by the large phase-space suppression from which pair production suffers. In particular, new heavy quarks can be produced singly in flavour-changing processes via the electroweak interaction through $q_i \bar{q}_j \rightarrow V^* \rightarrow q_k Q$ where $V = W, Z$. A comparison between the dominant production modes can be found in [10, 11] for fourth generation, and in [12] for vector-like quarks. Assuming order unity couplings, benchmark cross-sections have been evaluated for various mass scenarios and reproduced in Table II.

As described in [12], the leading contributions to vector-like T and B single production arise from $ud \rightarrow W^* \rightarrow jT$, $du \rightarrow W^* \rightarrow jB$, $qd \rightarrow Z^* \rightarrow jB$ and $qu \rightarrow Z^* \rightarrow jT$, where q denotes a valence quark parton and j a generic light quark jet. Unlike QCD pair

channel	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 14$ TeV
	$m_Q = 900 \text{ GeV}/c^2$	$m_Q = 1800 \text{ GeV}/c^2$
$pp \rightarrow W^* \rightarrow jX$	1.4	0.36
$pp \rightarrow W^* \rightarrow j\bar{X}$	0.037	0.0092
$pp \rightarrow W^* \rightarrow jT$	0.61	0.16
$pp \rightarrow W^* \rightarrow j\bar{T}$	0.052	0.013
$pp \rightarrow Z^* \rightarrow jT$	0.43	0.11
$pp \rightarrow Z^* \rightarrow j\bar{T}$	0.025	0.0064
$pp \rightarrow W^* \rightarrow jB$	0.69	0.18
$pp \rightarrow W^* \rightarrow j\bar{B}$	0.089	0.022
$pp \rightarrow Z^* \rightarrow jB$	0.18	0.047
$pp \rightarrow Z^* \rightarrow j\bar{B}$	0.034	0.0088
$pp \rightarrow W^* \rightarrow jY$	0.29	0.074
$pp \rightarrow W^* \rightarrow j\bar{Y}$	0.12	0.031

TABLE II. Electroweak single production cross-sections (in pb) as a function of the mass m_Q of the heavy quark, assuming order unity couplings as computed in [12]. In contrast, strong pair production $pp \rightarrow Q\bar{Q}$ yields 3.61 (0.63) fb for $m_Q = 900$ (1800) GeV/c^2 at $\sqrt{s} = 7$ (14) TeV.

production, the above processes however scale with the $Q - q$ quark coupling squared, and can thus be strongly suppressed if the associated mixings are negligibly small. On the other hand, Figs. 2 – 4 in [12] indicate that $\sigma(pp \rightarrow Q\bar{Q})$ falls off faster than the single production cross-sections as soon as m_Q reaches the TeV scale, while the electroweak production channels displayed in Table II take advantage from the possibly large m_Q^2/m_V^2 enhancement originating from the longitudinal polarisation of the gauge boson V . Such a behaviour can also be understood from the phase-space suppression arising from the presence of one or more heavy quarks in the final state, as well as from the decreasing parton luminosity for large x values at the LHC. Furthermore, given the difference in the PDFs of valence and sea quarks in the initial states, new heavy quarks are produced singly at a much higher rate than antiquarks for increasing m_Q .

We point out that the relative rates of the jQ and $j\bar{Q}$ channels strongly depend on the valence quark density in the initial state. While the u quark contributes more

than the d quark, the neutral current contributions are weaker than the charged current ones. Finally, we underline the absence of the tree-level processes $pp \rightarrow Z^* \rightarrow jQ$ for vector-like quarks involving exotic charges, given that they can only interact with other states via tree-level charged currents [12]. Although most of the above statements are model-dependent, we conclude that the large running energy of the LHC makes single electroweak production a promising discovery channel when considering new heavy quarks searches with $m_Q \gtrsim 1 \text{ TeV}/c^2$.

B. Decay

In the search of new fermions, the associated decay modes require careful attention. The exact partial width for a new sequential heavy quark Q decaying on-shell to a light quark q through a charged current can be written as

$$\Gamma(Q \rightarrow qW) = \frac{G_F m_Q^3}{8\pi\sqrt{2}} |\kappa_{Qq}|^2 f_2\left(\frac{m_q}{m_Q}, \frac{m_W}{m_Q}\right), \quad (1)$$

$$f_2(\alpha, \beta) = [(1 - \alpha^2)^2 + \beta^2(1 + \alpha^2) - 2\beta^4] \sqrt{[1 - (\alpha + \beta)^2][1 - (\alpha - \beta)^2]}, \quad (2)$$

where κ_{Qq} denotes the generic $Q - q$ quark coupling, equal to the CKM mixing matrix element V_{Qq} when considering a sequential new family of quarks. Interestingly, the width (1) holds for both chiral and vector-like quarks, given that all heavy-to-light charged current quark decays occur to be pure $V - A$ processes with identical rates [13]. If $m_Q \gg m_q$, the above partial width can be shown to reach the asymptotic form

$$\Gamma(Q \rightarrow qW) \simeq 170.5 \text{ MeV} \times |\kappa_{Qq}|^2 \times \frac{m_Q^3}{m_W^3}. \quad (3)$$

Considering a new heavy quark Q decaying exclusively via charged current 2-body decays, we evaluate in Table III the corresponding decay lengths, with $c\tau \simeq 2 \times 10^{-10} \text{ GeV}/\Gamma(\text{GeV}) \mu\text{m}$ and $|\kappa_{Qq}| = 1$. With increasing mass, the probability for a new heavy quark Q to decay weakly thus becomes more and more important as the individual lifetime decreases. However, small couplings to the lighter SM quarks strongly affect this statement as the total widths are suppressed by $|\kappa_{Qq}|^2$. As we will see in Section IID, this could lead to a very different phenomenology as the quarks Q , if very heavy, would form bound states and possibly decay hadronically.

$m_Q \text{ (GeV}/c^2\text{)}$	$\Gamma \text{ (GeV)}$	$c\tau \times 10^{12} \text{ (}\mu\text{m)}$
300	8.73 (2.39)	22.91 (83.85)
400	20.90 (11.14)	9.57 (17.96)
500	40.94 (27.86)	4.89 (7.18)
600	70.81 (54.52)	2.82 (3.67)
700	112.50 (93.06)	1.78 (2.15)
800	167.97 (147.43)	1.19 (1.38)
900	239.18 (213.57)	$83.62 (9.36) \times 10^{-1}$
1000	328.12 (299.46)	$6.10 (6.68) \times 10^{-1}$
1100	436.74 (405.05)	$4.58 (4.94) \times 10^{-1}$
1200	567.02 (532.31)	$3.53 (3.76) \times 10^{-1}$
1300	720.93 (683.21)	$2.77 (2.92) \times 10^{-1}$
1400	900.43 (859.72)	$2.22 (2.33) \times 10^{-1}$
1500	1107.5 (1063.79)	$1.81 (1.88) \times 10^{-1}$
1600	1344.1 (1297.4)	$1.49 (1.54) \times 10^{-1}$
1700	1612.2 (1562.5)	$1.24 (1.28) \times 10^{-1}$
1800	1913.8 (1861.1)	$1.05 (1.07) \times 10^{-1}$

TABLE III. Partial widths and decay lengths for a new heavy quark Q decaying to light quarks via on-shell charged currents $Q \rightarrow qW$, with $m_q = 0$ (173.2) GeV/c^2 and $|\kappa_{Qq}| = 1$, as computed from Eq. (1).

Several conclusions can already be drawn at this stage. As far as a heavy fourth quark family $(t', b')_L$ is concerned, we highlight that the ratios of the charged current decay rates to the lighter families only depend on the off-diagonal mixing elements. Assuming that the extended 4×4 CKM matrix is unitary, non-zero values for the

CKM mixing elements $|V_{Qq}|$ imply non-unity branching ratios for fourth generation quarks in general. If no assumption is made on the hierarchy of the $Q - q$ coupling strengths to weak currents, no exclusive flavour changing transitions should then be preferred for new heavy quarks.

Flavour Changing Neutral Currents lead to similar conclusions for models involving new vector-like quarks interacting with the SM families. Depending on their Yukawa couplings, they can indeed undergo tree-level transitions to lighter quarks and W , Z and Higgs bosons. Considering vector-like quarks $Q = T, B$ with $m_Q \gg m_q$, the neutral currents $Q \rightarrow qZ$ and $Q \rightarrow qH$ can occur with a rate of the same magnitude as given by (3), if they are allowed to mix with the light SM quarks q .

For non-chiral quarks decaying to Wq , Zq and Hq , long lifetimes can thus be expected in the $|\kappa_{Qq}| \simeq 0$

limit. Additionally, it is interesting to notice that $\Gamma(Q \rightarrow qZ)/\Gamma(Q \rightarrow qH) \simeq 1$ holds in the large mass limit $m_Q \gg m_q$ for most scenarios, while the charged-to-neutral current ratios $\Gamma(Q \rightarrow qW)/\Gamma(Q \rightarrow q(Z, H))$ approach either 2 or 0 depending on the vector-like representation [14].

If more than one new heavy quark is considered, and if they are allowed to decay into each other, the partial width (3) becomes inaccurate due to the possible competition with the heavy-to-heavy transitions $Q_1 \rightarrow Q_2 V^{(*)}$, where $V = W, Z, H$, depending on the model at hand. Indeed, if the decay rates of the daughter particles are significant with respect to the mass of the parent, the decay of an unstable particle is allowed through threshold effects, even if kinematically forbidden. For both chiral and vector-like quarks, real and virtual V emission near threshold proceed with the rate

$$\Gamma(Q_1 \rightarrow Q_2 V^{(*)}) = \frac{G_F^2 m_{Q_1}^5}{192\pi^3} |\kappa_{Q_1 Q_2}|^2 f_3\left(\frac{m_{Q_1}^2}{m_V^2}, \frac{m_{Q_2}^2}{m_V^2}, \frac{\Gamma_V^2}{m_V^2}\right), \quad (4)$$

$$f_3(\alpha, \beta, \gamma) = 2 \int_0^{(1-\sqrt{\beta})^2} dx \frac{[(1-\beta)^2 + x(1+\beta) - 2x^2]\sqrt{\lambda(1, x, \beta)}}{[(1-\alpha x)^2 + \gamma^2]}, \quad (5)$$

where $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ac$ [4]. While the $Q \rightarrow qV$ rates essentially depend on the $Q - q$ quark couplings, the heavy quark mass splittings $|m_{Q_1} - m_{Q_2}|$ drive the strength of the heavy-to-heavy transitions [11, 15]. If the quarks Q_1 and Q_2 belong to the same weak multiplet with a large mass splitting, the $Q_1 \rightarrow Q_2 V$ decay could be very rapid and dominate the other decay modes if there is no $|\kappa_{Q_1 Q_2}|$ suppression. On the other hand, the lightest partner can only decay into a SM family quark, and is thus plausibly long-lived for small mixings. Should this be the case, we will see in Section that the latter could hadronise, leading to a different decay phenomenology. This occurs specifically for $SU(2)_L$ vector-like singlets, which free quark decays can only proceed via non-zero mixing into the lighter generations.

As far as doublet and triplet representations are concerned, new vector-like partners should be very close in mass if one assumes that isospin conservation is respected. Although it may be broken by higher order corrections, such a degeneracy has been shown in [16] to require a mass difference between 70 and 110 MeV for non-chiral doublets, allowing for nanoseconds lifetimes. If their couplings to the lighter quarks are negligible, the partial widths for $X_{5/3}$, $T_{2/3}$, $B_{-1/3}$ and $Y_{-4/3}$ quarks are thus plausibly small.

Summarising these results, the range of the observable couplings to which long-lived particles searches are sensitive at the LHC can be evaluated. From the approxima-

tion (3), the partial decay length for a vector-like quark reads

$$\lambda \simeq 2 \text{ cm} \times \left(\frac{10^{-8}}{|\kappa_{Qq}|}\right)^2 \left(\frac{500 \text{ GeV}/c^2}{m_Q}\right)^3, \quad (6)$$

which gives an order of magnitude for the required $Q - q$ quark couplings to detect a new heavy quark Q . Assuming $m_Q \lesssim 1 \text{ TeV}/c^2$ and an experimental resolution of at least $25 \mu\text{m}$, we obtain that the heavy quark decays are prompt only if their associated couplings are above the 10^{-7} level. If $|\kappa_{Qq}| \lesssim 10^{-7}$, the corresponding decay lengths could be observed over a few tens of centimeters. In the limit of such small mixings with the SM fermions, it is thus natural to motivate searches for displaced vertices.

C. Classification of signatures

We now summarise the possible situations giving rise to the possibly observable signatures of long-lived quarks at the LHC.

The classification given in Table IV summarises the long-lived quark scenarios corresponding to the small mixing scenarios treated in this work, namely, κ_{Qq} couplings between 10^{-8} and 10^{-10} . Furthermore, if mixing with all SM quark families is permitted, direct searches should aim at being sensitive to all light quarks q in the

	(i) Short-lived	(ii) Intermediate	(iii) Long-lived	(iv) Stable
τ (s)	$\lesssim 10^{-14}$	$\gtrsim 10^{-14}$ $\gtrsim 10^{-10}$	$\gtrsim 10^{-10}$ $\gtrsim 10^{-9}$	$\gtrsim 10^{-9}$
Γ (GeV)	$\gtrsim 10^{-11}$	$\gtrsim 10^{-11}$ $\gtrsim 10^{-15}$	$\gtrsim 10^{-15}$ $\gtrsim 10^{-16}$	$\lesssim 10^{-16}$
$ \kappa_{Qq} $	$\gtrsim 10^{-7}$	$\gtrsim 10^{-7}$ $\gtrsim 5 \times 10^{-9}$	$\lesssim 5 \times 10^{-9}$ $\gtrsim 10^{-9}$	$\lesssim 10^{-9}$

TABLE IV. Possible decay signatures for new long-lived quarks ($m_Q = 1 \text{ TeV}/c^2$), as discussed in the text.

observed final states. Given that their interactions are allowed through arbitrary Yukawa couplings, the searches for long-lived vector-like quarks should be as inclusive as possible in order to cover the full spectrum of possibilities at the LHC. Such a program is important to set new constraints on the $Q \rightarrow qV^{(*)}$ decay modes, independently of any assumptions on the $Q - q$ mixing sector. The relative importance of the $Q \rightarrow (u, c, d, s)V$ channels is most relevant compared to the $Q \rightarrow (t, b)V$ charged currents, as no exclusive decay mode should be preferred for $V = W, Z, H$.

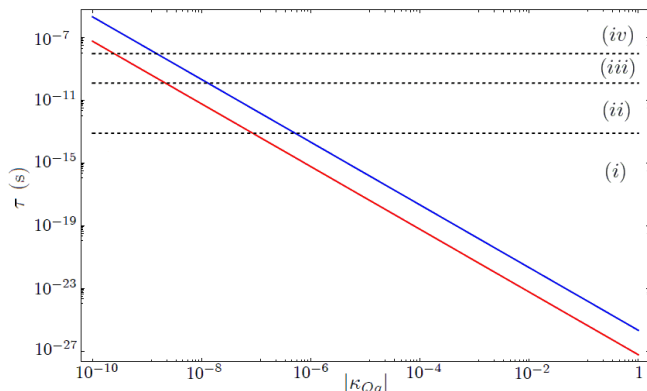


FIG. 1. Lifetime τ in seconds ($\gamma\beta \simeq 1$) for a sequential heavy quark Q decaying to the lighter families by emitting a real W boson, for $m_Q = 300 \text{ GeV}/c^2$ (in blue) and $m_Q = 1800 \text{ GeV}/c^2$ (in red). The four regions of interest refer to the conventions given in Table IV.

As illustrated in Figure 1, four cases for new long-lived quarks can be distinguished depending on their mixing parameters with the SM fermions. Firstly, if all couplings with the known SM fermions are larger than the 10^{-7} level, all heavy-to-light decays $Q \rightarrow qV$ are prompt, over distances smaller than $25 \mu\text{m}$. This defines the short-lived scenario (i), with no experimental difference compared to the direct searches.

The second scenario, (ii), arises for intermediate decay lengths ranging between a few microns and centimetric distances. If there is at least one light quark q such that $10^{-7} \lesssim |\kappa_{Qq}| \lesssim 10^{-9}$, displaced events could be observed, yet with a partial width suppressed by $|\kappa_{Qq}|^2$. Conse-

quently, if all the couplings but one are below the 10^{-7} level, a single exclusive channel would lead to a prompt decay signature with a partial width large enough to allow for short-lived heavy quarks.

A possible exception, though, is the case for new heavy multiplets with sizeable mass splittings, as allowed in extra generation models and possible extensions [11, 17–19]. If $m_{Q_1} \gtrsim m_{Q_2} + m_V$, the heaviest quark Q_1 can be short-lived and decay semi-weakly to $Q_2 V^{(*)}$. On the other hand, the lightest partner is likely stable if all its decay modes suffer severe suppression. If $m_{Q_1} \simeq m_{Q_2}$, all heavy-to-heavy transitions are suppressed and both quarks could be long-lived on detector scales.

For particles with decay lengths larger than the detector dimensions lies the narrow, yet unexplored region (iii) for which no strong limits can be set on long-lived heavy quarks. Details will be discussed in Section IID. Finally, if all heavy quarks couplings with the SM fermions are below the 10^{-10} level, the stable case (iv) becomes a relevant scenario, possibly in conjunction with displaced events. We emphasise that the scenarios (i), (ii) and (iii), for which prompt decays and displaced vertices could be observed with short, intermediate and large lifetimes respectively, only call for one of the allowed decay modes to fulfill the associated conditions. The stable scenario (iv), on the other hand, requires all decay lengths and partial widths to lie in the ranges given in Table IV.

In any case, the observability of the above signatures strongly depends on the allowed decay modes. As we will see in the next section, if all $Q - q$ quark couplings to the SM families are smaller than 10^{-2} , such new heavy fermions could hadronise. As a result, the annihilation decays and hadronic transitions between the formed bound states would dominate, while the single quark decay events might be suppressed.

D. Signatures for heavy stable particles : heavy quarkonia

Previously, we have discussed how displaced events could occur in the single quark decays transitions in the case of small $Q - q$ couplings. In this section, we describe the possibility for new heavy quarks to bind into hadrons if their lifetime is large enough, providing us with an interesting alternative for new signal searches at the LHC.

While new coloured particles with masses heavier than the top quark are usually assumed to decay as free particles, their possible formation into baryons and mesons is an important issue to consider in the case of small couplings with the SM fermions.

Should the partial widths $Q \rightarrow q(W, Z, H)$ be suppressed, the quark Q might be stable and hadronise. Assuming that the binding force in a fourth generation bound state is of Coulombic nature, the seminal condition

$$m_Q < 125 \text{ GeV} (100 \text{ GeV}) \times |V_{Qq}|^{-2/3} \quad (7)$$

was derived in [20] for $Q\bar{Q}$ ($Q\bar{q}$) formation. According to Eq. (7), new heavy quarks form hadronic states if their mixing with known quarks is sufficiently small. Mixings roughly smaller than 0.2 are typically required for 300 GeV/ c^2 new quarks to form bound states, which remains perfectly consistent with the current bounds from the electroweak precision observables. As shown on Figure 2 for a new up-like fourth generation quark t' , the electroweak precision fits typically restrict the mixing matrix element $|V_{t'b}| \simeq |V_{tb}|$ to be smaller than 10^{-1} for $m_{t'} > 700$ GeV/ c^2 . If lighter, the t' total width can be smaller than 10 MeV [11], thus allowing new chiral quarks to form bound states with nanosecond lifetimes.

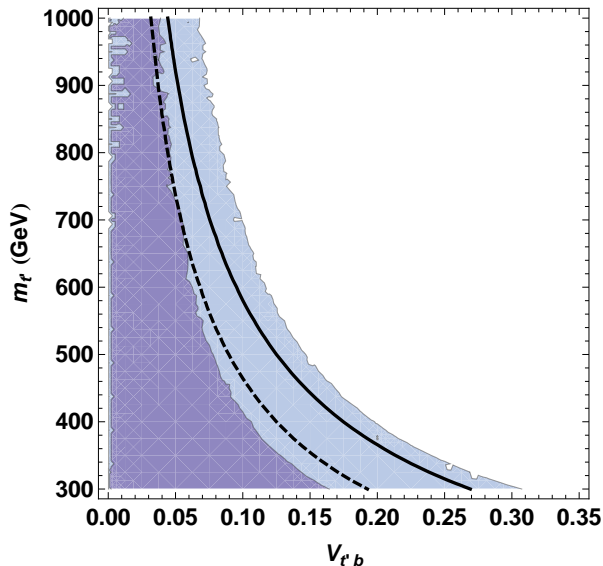


FIG. 2. Reproduction of the χ^2 fit of the oblique parameters S and T as given from Fig. 2 in [11], considering a chiral fourth generation quark t' . The upper limits at 68% (darker blue) and 95% (lighter blue) CL on the t' mass are depicted as a function of the CKM mixing $|V_{t'b}|$, freely varied over [300,800] GeV/ c^2 and [0,0.3], respectively. The solid (dashed) curve denotes the upper bound $m_{t'}(|V_{t'b}|)$ under which $t'\bar{t}'$ and $t'\bar{q}$ ($\bar{t}'q$) bound states can form, as defined by relation (7).

As far as non-chiral fermions are concerned, the electroweak precision constraints provide upper bounds on the mixing parameters, but are not as restrictive given that their effects decouple in the limit of large masses [22]. Although vector-like quarks are usually considered to couple dominantly to the heaviest third quark family (see [12, 23] for some exceptions), they are allowed, in principle, to mix with all up- (down-) type quarks [14].

In any case, $|\kappa_{Qq}| \lesssim 10^{-2}$ is used as a rule of thumb in most of the allowed vector-like representations [14]. Furthermore, large corrections to the CKM matrix elements are required to be small for $SU(2)_L$ singlets [24], doublets and triplets [25]. In this framework, the hadronic production of new bound states involving sequential or non-chiral quarks is a conceivable possibility at the LHC. Assuming that (7) is satisfied, their lifetime can be longer

than the hadronisation timescale $\Lambda_{QCD}^{-1} \simeq 10^{-23}$ s needed to build up new quarkonium resonances, open-flavour mesons and baryons [20].

If their formation is governed by the same strong interactions that are responsible for the existence of the ordinary hadronic spectroscopy, the associated mass spectrum can be determined from the known properties of low-energy hadron physics [26]. Considering a simplified model of QCD-like hadrons, new heavy quarks can form $Q\bar{Q}$ bound states (hereafter defined as η_Q) from induced, strongly attractive potentials. For instance, quarkonium formation can arise from Higgs boson exchange, as the corrections from Yukawa-type forces cannot be neglected for large quark masses [27, 28]. In [29], Hung detailed the numerical resolution of a general non-relativistic Higgs exchange potential, with interesting consequences on the associated scalar spectrum. More recently, Enkhbat et al. gave a preliminary discussion of the fourth generation Yukawa bound states phenomenology at the LHC, considering a ultra-heavy degenerate new quark family [30]. Although binding energies of Yukawa origin certainly provide a more consistent framework for a dedicated analysis, we restrict the present discussion to the context of Coulomb-like potential models, and assume that the short-distance behaviour of the quark-antiquark potential dominates (we refer the reader to [32] and [31] for previous and more exhaustive phenomenological reviews). In this context, the effects of the quarkonium wave function must be taken into account as we consider the corresponding production and decay modes. In perturbative QCD, the dominant contribution to η_Q production cross-section in pp collisions reads [32]

$$\sigma(pp \rightarrow gg \rightarrow \eta_Q) = \frac{\pi^2 \tau}{8m_\eta^3} \Gamma(\eta_Q \rightarrow gg) \left[\tau \frac{dL}{d\tau} \right]_{gg}, \quad (8)$$

$$\Gamma(\eta_Q \rightarrow gg) = \frac{8\alpha_s^2(m_\eta^2)}{3m_\eta^2} |R_S(0)|^2, \quad (9)$$

where $m_\eta = 2m_Q$, and $[\tau \frac{dL}{d\tau}]_{gg}$ denotes the gluon luminosity with $\tau = m_\eta^2/s$. The full NLO partonic cross-sections for the gg , $q\bar{q}$ and $q\bar{q}$ initiated reactions are provided in [33], and have been updated in [34]. Interestingly, they are all proportional to the square of the $Q\bar{Q}$ radial wave function R_S at the origin, which might drive the heavy quarkonium production cross-section $\sigma(gg \rightarrow \eta_Q)$ to be substantially smaller than $\sigma(gg \rightarrow Q\bar{Q})$. Indeed, the quarkonium production rate typically amounts to a few percent of the pair production cross-section [33–36].

Should it preferably hadronise into a quarkonium state, such a suppression should be taken into account when setting limits on a new long-lived heavy quark Q .

Depending on the ratio of its intrinsic width $\Gamma_{Q\bar{Q}}$ to the associated binding energy Δ_{η_Q} , three distinct cases must be considered for a given bound state. If it is strongly bound such that $\Gamma_{Q\bar{Q}} \lesssim \Delta_{\eta_Q}$, for example through new confining interactions going beyond the SM, the corresponding bound states will appear as quarko-

nium resonances while the constituent particles would not be directly observed. On the other extreme, if the width is much larger than the binding energy, namely, if $\Gamma_{Q\bar{Q}} \gtrsim \Delta_{\eta_Q}$, $Q\bar{Q}$ pair production could overtake η_Q production with little evidence of any resonance behaviour over the continuum. The interesting and most challenging case is certainly the intermediate regime $\Gamma_{Q\bar{Q}} \simeq \Delta_{\eta_Q}$. This can occur if the new fermions hadronise through the strong force, while the single particle decays are suppressed. The bound states then either undergo single quark decays or annihilate hadronically, with specific final state signatures.

We now give a brief and qualitative description of some of the expected η_Q final state signatures at the LHC, considering either a chiral or vector-like heavy quark Q . While similar results hold for all S - and P -wave quarkonium states, we limit our analysis to the case of a stable, neutral $J^{PC} = 0^{-+}$ pseudoscalar state η_Q . In particular, a 1S_0 quarkonium state formed from down-type fourth generation b' quarks is known to provide a possible candidate if the condition (7) is satisfied [34]. The latter is mainly produced through the gluon fusion process (9) with a production cross-section two orders of magnitude larger than the $J^{PC} = 1^{--}$ vector state [34]. If b' is the lightest fourth generation quark, a $b'\bar{b}'$ bound state can decay either through $q - b'$ family mixing with $q = u, c, t$, or to boson pairs. Whether the single quark decays would compete with the $\eta_{b'}$ hadronic modes depends on the heavy quark masses and mixings. If $m_{b'} > 1 \text{ TeV}/c^2$, a fourth-generation down-type quark dominantly decays into fermion-antifermion pairs if $|V_{qb'}| \gtrsim 10^{-2}$. For $m_{b'} < 1 \text{ TeV}/c^2$, the $\eta_{b'}$ total width lies below $1 \text{ GeV}/c^2$, and the quarkonium state decays proceed dominantly via the annihilation diagrams depicted in Figure 3 [34]. Decays to gauge boson pairs, fermion-antifermion pairs, gauge-Higgs and Higgs boson pairs can occur through γ, Z and H exchange in the s -channel, or proceed via quark mixing in the t - and u -channels, if allowed. While the processes involving charged currents are suppressed in the case of small quark couplings, the $\eta_{b'} \rightarrow WW$ mode is allowed at loop-level via the exchange of the $SU(2)_L$ partner t' , even if $|V_{tb'}| \simeq 0$. Decays to WW pairs are not allowed for $\eta_{T,B}$ bound states involving singlet vector-like quarks. Decays to Higgs boson pairs ($\eta_Q \rightarrow HH$) are forbidden by CP conservation in the case of $J^{PC} = 0^{-+}$ pseudoscalars.

An exhaustive study of the production and subsequent decays of the S - and P -wave quarkonium states of a heavy chiral quark is available in [32] and [37], where all the allowed production mechanisms and decay patterns have been thoroughly investigated. As an illustration, we compare in Figure 4 the branching ratios of the allowed decay modes for quarkonium states formed by a chiral fourth generation quark b' and a vector-like $B_{-1/3}$ isosinglet [37]. The quarkonium annihilation decay rates depend markedly on the mass scale.

In the chiral case, the main decay modes are ZH , gg , WW , ZZ , $Z\gamma$ and $\gamma\gamma$ respectively. The fermionic decays

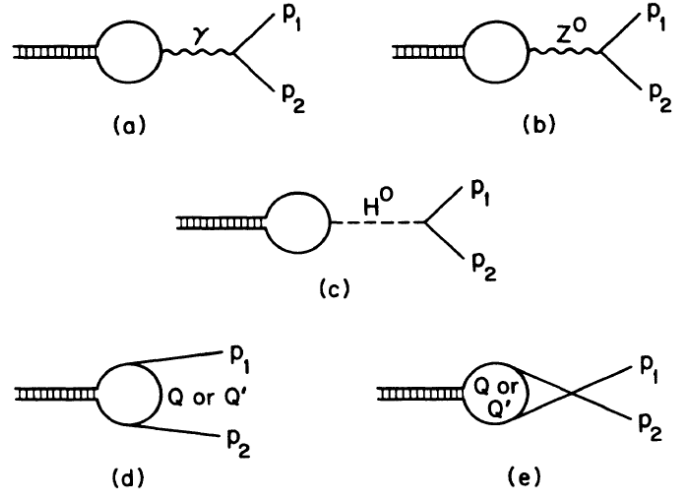


FIG. 3. First order diagrams for the $\eta_Q \rightarrow p_1 p_2$ decays, where p_1 and p_2 can be a gauge boson pair, a fermion-antifermion pair, a gauge-Higgs boson pair, or a pair of Higgs bosons. The strong decay mode $\eta_Q \rightarrow gg$ is also allowed but not shown above. The (a), (b), and (c) diagrams denote decays via γ , Z or H exchange in the s -channel, while (d) and (e) correspond to the $p_1 p_2$ decays involving quark exchange in the t - and u -channels. Figure from [32].

$\eta_{b'} \rightarrow q\bar{q}$ are also allowed if $|V_{qb'}| \neq 0$. For pseudoscalar $\eta_{b'}$ masses lighter than $450 \text{ GeV}/c^2$, the dominant annihilation mode proceeds via the strong interaction, *i.e.*, $\eta_{b'} \rightarrow gg$. Substantial decay rates to $q\bar{q}$ fermion pairs are allowed in case of large $Q-q$ couplings. For larger masses, the width into two gluons is decreasing, whereas the annihilation mode into ZH pairs takes over. This follows from the fact that the decay rates into Higgs and longitudinal gauge bosons are enhanced by the large Yukawa coupling of the heavy b' quark, so that the ZH branching ratio becomes sizeable for increasing masses. The latter channel then leads to a salient signature for heavy fourth generation bound states. Although it is suppressed below the percent level, the distinctive diphoton decay mode also provides a possible golden channel for discovery.

While fourth generation pseudoscalar quarkonia decays allow for striking signals, $T\bar{T}$ and $B\bar{B}$ bound states of vector-like quark singlets can only decay to gg , $\gamma\gamma$, γZ and ZZ pairs, as the $\eta_Q \rightarrow ZH$ mode is absent [37]. This follows from the fact that the ZH mode proceeds through the axial part of the neutral current coupling, which in turn is proportional to the third component of the weak isospin. Only $\gamma\gamma$, $Z\gamma$ and ZZ would then signal the visible hadronic modes with branching ratios of about 10^{-4} . $T\bar{T}$ and $B\bar{B}$ bound states of $SU(2)_L$ vector-like singlet quarks are thus hardly observable at the LHC as the gluon mode dominates. On the other hand, T and B vector-like doublet (triplet) partners with non-vanishing weak isospin can have large branching ratios to ZH via γ , Z or H exchange in the s -channel. The η_X and η_Y

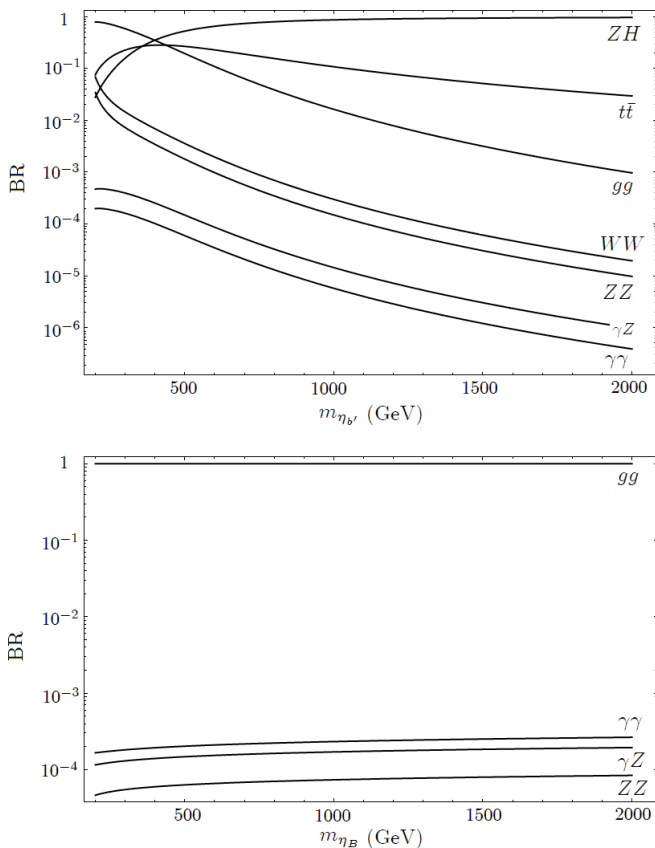


FIG. 4. Branching ratios as given in [37] for η_Q quarkonium, considering a chiral b' quark (top) and a down-type singlet vector-like B quark (bottom), with $m_H = 125 \text{ GeV}/c^2$. $|V_{tb'}| \simeq 1$ is assumed in the fourth generation case.

quarkonia provide a noticeable exception, given that the exotic quarks $X_{5/3}$ and $Y_{-4/3}$ do not couple to neutral currents at tree-level. Since they only mix with the other states via charged currents, the annihilation modes including γ , Z and H exchange are thus forbidden for η_X and η_Y , which then mainly decay to gg , WW and to the suppressed $\gamma\gamma$ modes.

E. Signatures for heavy stable particles : open-flavour mesons

While $Q\bar{Q}$ quarkonium resonances might be challenging to observe, the possibility for “open-flavour” hadrons $Q\bar{q}$ ($\bar{Q}q$) and Qqq ($\bar{Q}\bar{q}\bar{q}$), with q being a light SM quark, also cover a broad spectrum of new heavy mesons and baryons to search for. Should they be produced at the LHC, such states can form by capturing a light quark partner from the vacuum. As they pass through the detector, they can transform into various slowly-moving heavy states. Assuming that they hadronise with u , d and s quarks after being produced, Table V lists the corresponding stable mesons and baryons.

The properties of new hypothetical fourth generation quarkonium and open-flavour mesons have been examined previously in [38] considering large- N expansion techniques. In [39], their masses and decay constants have been estimated from the experimental measurements of the ordinary $b\bar{b}$ ($c\bar{c}$) hadron masses, using the QCD sum rules. Interestingly, both approaches indicate that the corresponding spectra share numerous features with most of the scenarios predicting stable bound states of heavy quarks beyond the Standard Model, depending on their masses, charges and angular momenta.

If they decay within the detector, the interactions of such open-flavour mesons with the material occur to be similar to that of R-hadrons, *i.e.*, stable hadrons composed of a supersymmetric particle and at least one SM quark (see [40, 41] and references therein for related works). The 1/2 difference in spin with respect to stop hadrons has little impact on the search strategies, which depend mostly on the interactions between the lighter quarks and the detector. This is in substance the description given by the spectator model [42, 43], for which the allowed transitions of heavy and light quarks within a given bound state are known to be flavour and spin independent [44, 45]. In this context, the heavy quark Q can be considered as a source of kinetic energy which sole function is to give mass and momentum to the underlying hadron. Such new heavy bound states then behave as rather passive objects, consisting of a non-interacting heavy component, accompanied by lighter constituents (u and d quarks, mostly). While the partons are being scattered within the detector, their cross-sections vary with their inverse mass in perturbative QCD [6, 26]. A heavy $Q\bar{q}$ (Qq) bound state is then expected to suffer small energy losses when interacting with the detector, given that only its light quark half is responsible for the hadronic interactions with the detector.

We list in Table VI the various allowed $2 \rightarrow 2$ and $2 \rightarrow 3$ transitions involving meson-to-meson and meson-to-baryon conversions. In general, these interactions lead to simultaneous pion emission as the initial mesons convert into slowly-moving baryons.

While they interact with the detector, most of the new states suffer multiple scattering and convert into baryons, allowing for Quu , Qud and Qdd states, as new heavy mesons are kinematically favoured to increase their baryon number by emitting one or more pions [26]. Due to the lack of these in the material, the reverse reaction is known to be less favoured.

Interestingly, new mesons which convert at the beginning of the scattering chain could generate tracks with “dashed-lines”, signalling possible baryonic or electric charge exchange. Indeed, $Q\bar{q}$ and $\bar{Q}q$ bound states traversing a medium composed of light quarks likely flip their electric charge, frequently interchanging their parton constituents with those of the material nuclei. Eventually, they could leave the detector as heavy stable neutral particles and hence not be observable in muon detectors. The modeling of the nuclear interactions of

Charge	Mesons	Baryons
$Q = 0$	T\bar{u} , T\bar{u} , B\bar{d} , B\bar{d} , $B\bar{s}$, $\bar{B}s$	Tdd, Tds, Tss , Bud , $\bar{B}\bar{u}\bar{d}$, Bus , $\bar{B}\bar{u}\bar{s}$, Yuu , $\bar{Y}\bar{u}\bar{u}$
$Q = 1$	X\bar{u} , T\bar{d} , $T\bar{s}$, B\bar{u} , Y\bar{d} , $\bar{Y}s$	Xdd, Xds, Xss , Tud , Tus , Buu , $\bar{B}\bar{d}\bar{d}$, $\bar{B}\bar{d}\bar{s}$, $\bar{B}\bar{s}\bar{s}$, $\bar{Y}\bar{u}\bar{d}$, $\bar{Y}\bar{u}\bar{s}$
$Q = 2$	X\bar{d} , $X\bar{s}$, Y\bar{u}	Xud , Xus , Tuu , $\bar{Y}\bar{d}\bar{d}$, $\bar{Y}\bar{d}\bar{s}$, $\bar{Y}\bar{s}\bar{s}$
$Q = 3$	-	Xuu

TABLE V. $Q\bar{q}$ ($\bar{Q}q$) mesons and Qqq ($\bar{Q}\bar{q}\bar{q}$) (anti-)baryons involving $Q = X_{5/3}, T_{2/3}, B_{-1/3}$ and $Y_{-4/3}$ vector-like quarks. The states in bold font are hadrons which yields are expected to be substantial at the LHC. For simplicity, only the neutral and positively charged hadrons are displayed.

Meson-to-Meson $2 \rightarrow 2$ processes:	Meson-to-Baryon $2 \rightarrow 2$ processes:
Charge exchange:	Baryon exchange:
$Q\bar{u} + p \longleftrightarrow Q\bar{d} + n$	$Q\bar{u} + n \rightarrow Qud + \pi^-$
	$Q\bar{u} + n \rightarrow Qdd + \pi^0$
	$Q\bar{u} + p \rightarrow Quu + \pi^-$
	$Q\bar{u} + p \rightarrow Qud + \pi^0$
Elastic scattering:	
$Q\bar{q} + p/n \rightarrow Q\bar{q} + p/n$	$Q\bar{d} + n \rightarrow Qud + \pi^0$
	$Q\bar{d} + n \rightarrow Qdd + \pi^+$
	$Q\bar{d} + p \rightarrow Quu + \pi^0$
	$Q\bar{d} + p \rightarrow Qud + \pi^+$
Meson-to-Meson $2 \rightarrow 3$ processes:	Meson-to-Baryon $2 \rightarrow 3$ processes:
Inelastic scattering:	Baryon exchange:
$Q\bar{u} + n \rightarrow Q\bar{d} + n + \pi^-$	$Q\bar{u} + n \rightarrow Qud + \pi^- + \pi^0$
$Q\bar{u} + n \rightarrow Q\bar{u} + n + \pi^0$	$Q\bar{u} + n \rightarrow Qdd + \pi^- + \pi^+$
$Q\bar{u} + n \rightarrow Q\bar{u} + p + \pi^-$	$Q\bar{u} + n \rightarrow Qdd + \pi^0 + \pi^0$
$Q\bar{u} + p \rightarrow Q\bar{d} + p + \pi^-$	$Q\bar{u} + p \rightarrow Quu + \pi^- + \pi^0$
$Q\bar{u} + p \rightarrow Q\bar{u} + p + \pi^0$	$Q\bar{u} + p \rightarrow Qud + \pi^- + \pi^+$
$Q\bar{u} + p \rightarrow Q\bar{u} + n + \pi^+$	$Q\bar{u} + p \rightarrow Qud + \pi^0 + \pi^0$
$Q\bar{u} + p \rightarrow Q\bar{d} + n + \pi^0$	$Q\bar{u} + p \rightarrow Qdd + \pi^+ + \pi^0$
$Q\bar{d} + n \rightarrow Q\bar{u} + n + \pi^+$	$Q\bar{d} + n \rightarrow Qud + \pi^- + \pi^+$
$Q\bar{d} + n \rightarrow Q\bar{d} + n + \pi^0$	$Q\bar{d} + n \rightarrow Qud + \pi^0 + \pi^0$
$Q\bar{d} + n \rightarrow Q\bar{u} + p + \pi^0$	$Q\bar{d} + n \rightarrow Qdd + \pi^0 + \pi^+$
$Q\bar{d} + n \rightarrow Q\bar{d} + p + \pi^-$	
$Q\bar{d} + p \rightarrow Q\bar{u} + p + \pi^+$	$Q\bar{d} + p \rightarrow Quu + \pi^- + \pi^+$
$Q\bar{d} + p \rightarrow Q\bar{d} + p + \pi^0$	$Q\bar{d} + p \rightarrow Quu + \pi^0 + \pi^0$
$Q\bar{d} + p \rightarrow Q\bar{d} + n + \pi^+$	$Q\bar{d} + p \rightarrow Qud + \pi^0 + \pi^+$

TABLE VI. Meson-to-Meson and Meson-to-Baryon processes for $Q\bar{u}$ and $Q\bar{d}$ mesonic states, where $Q = X_{5/3}, T_{2/3}, B_{-1/3}, Y_{-4/3}$ and $q = u, d$. Similar transitions can be obtained for the charge conjugated processes involving $\bar{Q}q$. Assuming that the cross-sections for all the transitions are of the same order of magnitude, Meson-to-Baryon processes to Qud states are more likely than those involving Quu and Qdd in the final state.

new heavy hadrons traveling through matter, a survey of which is given in [26, 46], actually favours scenarios with significant charge suppression if heavy open-flavour mesons have a sizeable probability to transform into neutral particles while traversing the detector. This poses a serious challenge for the experimental searches, since the most conservative scenarios assume a complete charge suppression where 100% of the produced hadrons become

neutral before reaching the muon detectors. Taking a specific example, we consider pair-produced $T_{2/3}$ quarks hadronising into the heavy states $T\bar{q}$ and $\bar{T}q$ immediately after production. For convenience, we assume that a majority ($\gtrsim 90\%$) of the new heavy quarks initially hadronise into mesons, while a smaller amount ($\lesssim 10\%$) form baryons [6]. As they interact farther in the detector, most of the $T\bar{q}$ mesons eventually exit the detector as $T\bar{u}$

and $T\bar{d}$ mesonic states, or as Tud baryons. Baryon-to-meson conversions are allowed as well, as these states can also annihilate back into $T\bar{u}$ and $T\bar{d}$ mesons, yet with a smaller rate [47]. Regarding bound states of vector-like antiquarks, $\bar{T}q$ mesons unlikely give rise to antibaryons, but can still flip their charge through the exchange of u and d quarks with the material. Possibly large flavour fractions for $\bar{T}u$ and $\bar{T}d$ can thus be expected in the detector, with a negligible amount of $\bar{T}\bar{q}\bar{q}$ antibaryons.

After travelling through the detectors a few nuclear lengths away from the production vertex, the novel hadrons transform in roughly 100% to the positively charged baryon Tud , whereas one half of the $\bar{T}-$ states thus transform into $\bar{T}u$ mesons, and the other half in $\bar{T}d$. The corresponding hadronic flavour decompositions, evaluated as a function of the penetration depth in the detector, can be read from fig. 5 of [26] for R-hadrons involving stable scalar top and antitop quarks. We notice that similar results are obtained when replacing stop \tilde{t} squarks by stable quarks T of equal mass. The Tud , $T\bar{u}$ ($\bar{T}u$) and $T\bar{d}$ ($\bar{T}d$) states are then expected to retain the largest flavour composition fractions when considering penetration depths larger than 3 meters, and are thus the most likely observable states, which we emphasised in bold font in Table V.

Except for Yuu and $\bar{Y}\bar{u}\bar{u}$, it is interesting to notice that none of the states listed in Table V is neutral if involving vector-like quarks with exotic charges. The corresponding bound states might give rise to possibly large fractions of slowly moving charged particles Xud and Yud with $Q = +2e$ and $-e$ respectively, accompanied by a small amount of $X\bar{u}$, $X\bar{d}$, $Y\bar{u}$ and $Y\bar{d}$ mesons (and charge conjugates). These particles are all electrically charged as they go across the detector, emitting charged and neutral pions in the process together with losing small amounts of energy. Given the small expected interaction cross-section from the Meson-to-Baryon transitions, the processes shown in Table VI leave small energy deposits in the calorimeters, of the order of $O(1)$ GeV [6]. On the other hand, such stable hadrons would lead to observable tracks due to the ionisation energy losses, allowing for signatures similar to slow-moving muons with high transverse momentum. Searches for stable charged particles, if adapted to such a case, thus provide a promising strategy to rule out the possibility for novel exotic quarks with large lifetimes. Given these very specific signals, the aforementioned signatures can certainly be discriminated at the LHC.

III. EXPERIMENTAL ASPECTS

In this section, we review the past and current experimental searches for new long-lived quarks. Their possible limitations are then discussed, as novel heavy quarks might lead to signatures involving displaced vertices, new hadronic bound states, or decays happening outside of the detector acceptance.

A. Previous searches at Tevatron

The searches undertaken at the Tevatron resulted in already stringent mass bounds on long-lived heavy quarks, yet not without assumptions. Looking for long-lived parents of the Z boson in displaced vertices from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, CDF set limits on the cross-section of a fourth generation charge $-1/3e$ quark as a function of its lifetime with an integrated luminosity of 90 pb^{-1} [48]. Isolated electron-positron pairs originating from Z decays were searched for in the exclusive channel $b' \rightarrow bZ$ with $m_{b'} > m_Z$. Finding no evidence for new long-lived particles, CDF excluded $m_{b'} < 148 \text{ GeV}/c^2$ for $c\tau = 1 \text{ cm}$ at 95% CL. This limit drops to $m_Z + m_b \simeq 96 \text{ GeV}/c^2$ if $c\tau > 22 \text{ cm}$ or $c\tau < 0.009 \text{ cm}$. Previously, the D0 collaboration already ruled out the range $m_Z/2 < m_{b'} < m_Z + m_b$ from $b' \rightarrow b\gamma$ searches in [49] for all proper lifetimes, while a b' quark with a mass lower than $m_Z/2$ was previously dismissed by the LEP direct searches [50]. Within a 90 pb^{-1} data sample of $p\bar{p}$ collisions recorded during 1994-95, CDF performed a search for low velocity massive charged stable particles leaving large amounts of energy in the calorimeters [51].

Assuming a muonlike penetration and searching for an anomalously high ionisation energy loss signature, the data was found to agree with background expectations, and upper limits of the order of 1 pb were derived on the production cross-section. Sensitive to long-lived fourth generation quarks scenarios, the lower bounds $m_{b'} > 190 \text{ GeV}/c^2$ and $m_{t'} > 220 \text{ GeV}/c^2$ have been obtained for $q = -1/3e$ and $q = 2/3e$ stable quarks respectively, with no observed excess over background. More recently, D0 studied a 1.1 fb^{-1} data sample and looked for $Z \rightarrow e^-e^+$ decays assumed to follow from a long-lived b' quark parent with $\text{BR}(b' \rightarrow bZ) = 100\%$ [52]. Assuming that the electromagnetic showers were originating from the same vertex, the analysis found no hint away from the $p\bar{p}$ interaction point. D0 excluded $m_{b'} < 190 \text{ GeV}/c^2$ at the 95% confidence level for decay lengths between 3.2 mm and 7 m. With the same integrated luminosity, CDF excluded $m_{b'} < 268 \text{ GeV}/c^2$ at 95% CL, considering a long-lived b' quark decaying exclusively into a Z boson and a b jet [53]. However, it has been emphasised in [54] that the assumption $\text{BR}(b' \rightarrow bZ) = 100\%$ is inaccurate for $m_{b'} > 255 \text{ GeV}/c^2$, given that the b' decay mode $b' \rightarrow tW$ should take over if $m_{b'} > m_t + m_W$. Furthermore, the processes $b' \rightarrow (u, c)W$ were hinted to proceed with non-negligible rates, leading to an even lower branching ratio. Indeed, even if the $b' \rightarrow tW$ decay dominates, the aforementioned mass limits depend sensitively on the CKM mixing elements between the fourth and the first three generations. If non-zero couplings between the fourth and the lighter quarks are allowed, the CDF lower bound on $m_{b'}$ can be significantly affected.

Additionally, it is known that the above CDF limits do not apply for long-lived heavy quarks decaying between roughly 1 cm and 3 m within the detector [54]. Should their couplings to SM quarks lie in the corresponding

range $4.5 \times 10^{-9} - 7.8 \times 10^{-8}$, there exists no bounds on the t' and b' masses in this uncovered region. For decay lengths larger than the detector dimensions, the lower bounds drop to $m_{t'} > 220 \text{ GeV}/c^2$ and $m_{b'} > 190 \text{ GeV}/c^2$ from the stable quark searches [51, 52]. Although most experiments require the quarks to decay within a few centimeters from the beam pipe, this is generally not the case for new heavy particles having very small mixings with the SM quarks. This issue should be treated carefully at the LHC.

B. LHC

1. Limitations of direct searches

While dedicated searches for long-lived bound states of vector-like heavy quarks are still missing at the LHC, various searches for heavy quarks of zero lifetime have already been performed by the ATLAS and CMS experiments. In this section, we discuss how the results of searches for prompt production could be reinterpreted for lifetimes larger than 10^{-10} s .

The main aspects of reinterpreting these results are the branching ratios to the investigated final states, which may be different in alternative models, and of course the lifetime of the heavy particle.

Considering here a specific example, the current best limit on b' production, published by the CMS collaboration, excludes production cross-sections of $\sigma > 0.1 \text{ pb}$ at the 95% confidence level with an integrated luminosity of 4.9 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ [55], assuming a branching ratio $\text{BR}(b' \rightarrow tW) = 100\%$. As we have seen in Section II B, the assumption of exclusive branching ratios is not generally valid for new heavy quarks. Nevertheless, the fraction to which a hypothetical signature occurs can be used to recalculate the cross-section limit in the most naïve approximation

$$\sigma_{\text{true}} = \sigma_{\text{excluded}} \times \frac{\text{BR}_{\text{assumed}}}{\text{BR}_{\text{true}}}, \quad (10)$$

where σ_{excluded} is the excluded cross-section under the assumption of $\text{BR}_{\text{assumed}}$, and BR_{true} is the branching ratio in the given model.

While this statement is certainly trivial, the reinterpretation for longer lifetimes requires more thought. In particular, the implicit assumption of heavy quarks decaying promptly at the production vertex is valid only for very short lifetimes. If these particles form bound states and propagate certain distances before their decay, they can potentially escape the direct searches. In such a scenario, the published limits could be considerably weaker, depending on the particle's lifetimes, simply because they would fly too far to be detected at the primary vertex.

For intermediate lifetimes with displaced decay vertices within the detector volume (cfr. the region (ii) discussed in Section II C), a recalculation of the published limits

can be attempted. Assuming an exponential decay function, a fraction of the decays will always happen in the vicinity of the beam line, so that the prompt searches will pick them up. Based on this fraction, one can recalculate the limits as a function of the heavy quark lifetime. However, in order to do this correctly, one requires the exact selection efficiency as a function of the displacement from the beam line. Unfortunately, such information has not been made available by the experiments. Still, it can be estimated from an educated guess under specific assumptions. For instance, the analysis in [55] applies b -jet tagging, which requires high-quality tracks to originate within the inner detector volume. The CMS innermost part, the pixel detector consists of three barrel layers with the innermost layer at a distance of 4.4 cm from the beam line. This represents the technical limitation to this analysis, so that we can assume that the selection efficiency vanishes at a transverse displacement of around 4 cm.

Even in analyses without application of b -jet tagging, stringent quality cuts are usually required to select reconstructed detector objects originating from the primary vertex. One of the motivations for these requirements is the rejection of pileup. Jets from displaced decays which do not point to the production vertex are mostly removed by the pileup cleaning procedures. We therefore make the assumption that events are kept in the direct searches if the decay happens at less than 4 cm from the primary interaction vertex, and lost otherwise. The fraction of the lost events can be determined from the distance these particles travel before their decay. This distance d depends on the mass, the momentum and the proper lifetime τ . It is defined in the laboratory frame as $d = \gamma \cdot \beta \cdot c \cdot \tau$. The fraction is obtained by convoluting d with an exponential decay function and the momentum spectrum which determines γ and β .

We take the momentum spectrum of pair-produced heavy quarks as predicted by the MadGraph [56] Monte Carlo generator. The assumed center of mass energy is $\sqrt{s} = 8 \text{ TeV}$. The momentum is needed for a precise calculation of the decay distance on an event by event basis because the velocity may be significantly smaller than c . The p_T distribution for various quark masses is shown in Figure 5.

Due to the very high masses these particles can be slowly moving. The distribution of the velocity in units of c is shown in Figure 6. It is visible that the average velocity, for instance for $m_Q = 1000 \text{ GeV}/c^2$ is about $0.6c$.

This simulation assumes that the production mechanism and kinematics are independent of the lifetime of the particle. Possible limitations of that assumption are discussed in Section III B 4. Calculating the distribution of decay vertices in the detector frame, we then obtain the fraction of decays outside of the geometrical acceptance of 4 cm as a function of the proper lifetime τ . Table VII summarises our results for a few benchmark points in the parameter space. The results are displayed as a

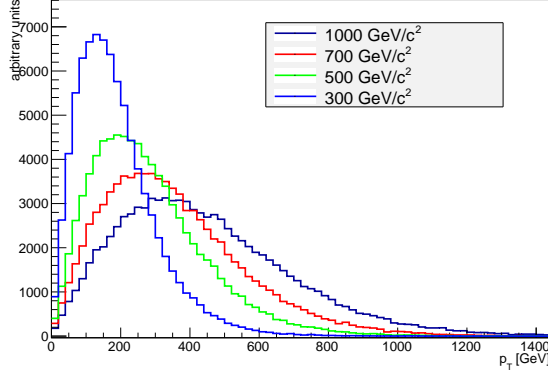


FIG. 5. Transverse momentum distribution of pair-produced heavy quarks as predicted by MadGraph.

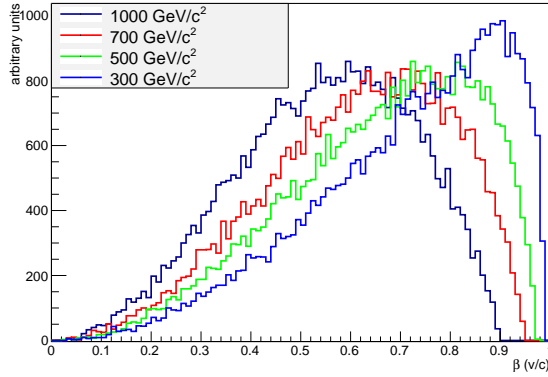


FIG. 6. Velocity distribution of pair-produced heavy quarks in units of $\beta = v/c$ as predicted by MadGraph.

function of the proper lifetime in Figure 7.

Lifetime	10^{-10} s	10^{-9} s	10^{-8} s
$m = 300 \text{ GeV}/c^2$	32%	86.5%	98.5%
$m = 500 \text{ GeV}/c^2$	26%	84.1%	98.3%
$m = 700 \text{ GeV}/c^2$	21%	82.3%	97.9%
$m = 1000 \text{ GeV}/c^2$	16%	79.4%	97.5%

TABLE VII. Fraction of rejected decays of heavy quarks outside of the geometrical acceptance of 4 cm around the primary interaction vertex for three different lifetimes and four different heavy quark masses.

We can now immediately conclude that direct searches are only valid for lifetimes which are considerably shorter than about 10^{-10} s, otherwise the particles would propagate too far and be rejected by the selection criteria. We also stress that this result is relatively independent of the particle masses within our approximations.

The published limits on the heavy quark production

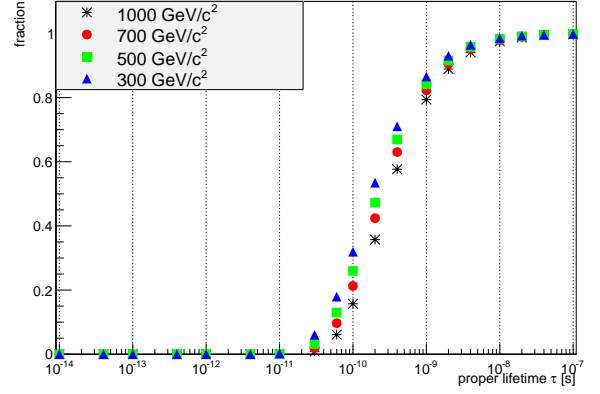


FIG. 7. Fraction of rejected decays of heavy quarks outside of the geometrical acceptance of 4 cm around the primary interaction vertex as a function of the proper lifetime τ .

cross-sections can be simply reinterpreted in the region $10^{-8} \text{ s} < \tau < 10^{-10} \text{ s}$ by

$$\sigma_{\text{true}} = \sigma_{\text{excluded}} \times (1 - f) \quad (11)$$

where σ_{excluded} and σ_{true} are the published and recalculated limits and f is the fraction of lost events given in Table VII and Figure 7. The recalculation of the mass limits can then be done by comparing the recalculated cross-sections with predicted cross-sections as a function of the mass.

2. Displaced vertices

The immediate question that arises from the previous results is whether lifetimes larger than 10^{-10} s are covered by dedicated searches for long-lived particles, either through displaced vertices or signatures of stable particles propagating through the full detector.

As already mentioned above, dedicated analyses for long-lived vector like quarks have not been done at the LHC, but reinterpretations of other searches may be possible.

Displaced topologies have been searched for at LHC and published, for instance in [57] and [58]. These searches are not directly applicable to heavy quarks for different reasons which will be discussed in this section. The sensitivity of these searches is impressive as the excluded cross-sections are comparable with predicted heavy quark production cross-sections, so it is worthwhile discussing this in more detail.

The CMS analysis [57] looks for heavy, long-lived χ bosons decaying to di-leptons $\chi \rightarrow l^+ l^-$. This analysis is feasible thanks to the CMS track reconstruction algorithm which is able to identify very displaced tracks not originating from the primary interaction vertex. Tracks of two oppositely charged leptons are fit to a common

vertex, requiring the vertex to fulfill $\chi^2/n < 5$ where n is the number of degrees of freedom. With this method transverse displacements up to 50 cm from the beam line can still be reconstructed. This analysis is able to put limits on production cross-sections of $\sigma \times \text{BR} < 10^{-3}$ pb at 95% C.L. The $b' \rightarrow tW$ and $B \rightarrow tW$ decays, for instance, can lead to displaced di-lepton vertices as well, because both W bosons can decay leptonically. For a mass of $m_{b'} = 500 \text{ GeV}/c^2$ the predicted $b'\bar{b}'$ production cross-section is $\sigma = 0.310 \text{ pb}$ [59], which is clearly in the vicinity of the analysis sensitivity. However, in this analysis, the momentum of the vertex is required to be parallel to the vector pointing from the primary vertex to the χ boson decay vertex.

This requirement is actually the limiting criterion which makes the result insensitive to heavy quarks. Due to the presence of the neutrinos and of the b -quark jet in the decay cascade, the momentum of the di-lepton vertex will not be parallel to the vector pointing from the primary to the secondary vertex. Consequently, di-leptonic decays of heavy quarks are mostly rejected in this analysis.

We suggest a straightforward extension of this analysis removing this collinearity cut. The side effect would be increased background levels because the purpose of this cut is its rejection. It is a priori not trivial to predict the amount of additional background from the available information, nor obvious whether the additional backgrounds can be discriminated with other methods. Given the high sensitivity of this analysis, as reported above, it should still be feasible to reach exclusions of heavy quark production cross-sections.

Another component that would be necessary to derive limits on heavy quark production from displaced vertex searches is the Monte Carlo simulation of the signal process. The interaction of these heavy particles with the detector material and the efficiency of their reconstruction and selection need to be estimated in order to facilitate the calculation of limits. Difficulties may arise from missing implementations of certain exotic models in the simulation software. Existing simulations of heavy stable particles such as those of R-hadrons may provide good approximations though [26].

A displaced vertex analysis has also been performed by the ATLAS collaboration [58], yet following a slightly different strategy. Displaced vertices are reconstructed in an inclusive way, using all displaced tracks in the event as potential seeds. In contrast to CMS, where only opposite-sign di-muon vertices have been used, the ATLAS approach requires at least four tracks at the vertex and a vertex mass of at least $10 \text{ GeV}/c^2$. Requirements on momentum collinearity have not been made, so heavy quark decays will in principle be selected. To ensure a good fit quality, only vertices within the fiducial barrel pixel detector volume are considered, which means that transverse displacements up to 18 cm are considered. In addition, one muon with $p_T > 45 \text{ GeV}/c$ is required to be present in the event. The muon is not required to

originate from the displaced vertex in order to enhance sensitivity for models in which it arises from the proton-proton vertex. This analysis has been carried out in the context of long-lived supersymmetric particles, and limits on $\sigma \cdot \text{BR}$ have been derived. Depending on particle type and lifetime, the limits are in the range of 0.2 to 10 pb using an integrated luminosity of only 33 pb^{-1} at $\sqrt{s} = 7 \text{ TeV}$. With more data we can expect this analysis to become sensitive to heavy quark decays as well. However, no attempt has been made to put this into the context of heavy quark searches. So the obvious suggestion is to extend the theoretical models covered by this analysis to heavy quarks as well. Also in this case the Monte Carlo simulation of the signal process is the central ingredient for an extension of the coverage to heavy quarks.

3. Heavy Stable Charged Particles

For very long-lived scenarios, the new heavy states do not decay, but travel through the full detector. In the following we review recent results by CMS [60] along with an assessment of their relevance for HSCPs.

The main identification criteria for HSCPs are high momentum, high ionization and long time of flight (TOF). The energy loss dE/dx along the track is calculated from the charge deposits in the silicon tracker, while the TOF is obtained from the arrival time in the muon system. These quantities are uncorrelated for SM particles. This noncorrelation is used to estimate the background yields in signal-depleted regions.

Models of charge suppression due to interaction of HSCPs with the detector material are considered as well. If charged particles become neutral while propagating through the detector they do not reach the muon chambers. The TOF criterion cannot be used in this case. Therefore, the results have also been estimated without the TOF requirement at the cost of weaker exclusion limits.

The obtained limits for a given mass can be very different depending on the assumed particle type. This is due to the predicted kinematics of the particle and its expected detector signal. For instance, the limit on pair production of a scalar top quark with a mass between 300 and $800 \text{ GeV}/c^2$ is $\sigma < 3 \text{ fb}$ for an integrated luminosity of 5 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$.

Limits for long-lived heavy quarks have not been considered explicitly, unfortunately. However, as an approximation, we make the assumption that a long-lived bound state of a stop would behave similar or equal to a bound state of a heavy up-type quark [26]. This concerns both the interaction with the detector material and the production mechanism which is assumed to proceed via the strong interaction. It is then possible to use the stop exclusion limits directly for stable heavy quarks. Limitations in that assumption are discussed in Section III B 4.

The predicted production cross-sections of heavy quarks are quite large for low masses (Section II A).

Even with a large systematic safety margin, these cross-sections can be considered to be excluded by the HSCP searches. Extremely heavy quark masses of the order of $m_Q \approx 1 \text{ TeV}/c^2$ are not yet excluded though, neither in direct searches for prompt decays nor in long-lived searches.

To make a quantitative statement about the excluded lifetimes by the HSCP searches, we repeat our simulation from Section III B 1. To be detected by these analyses, the particles have to traverse the full tracking devices, and the muon chambers for the combined tracker+TOF analysis. The CMS tracker has a length of about 6 m and a diameter of 2.8 m [61]. We can calculate the fraction of decays inside the tracker volume and assume that these decays will not be reconstructed in the HSCP analyses because of missing hits in the outermost tracker layers.

Tables VIII and Figure 8 summarise our estimations for a few benchmark points and as a function of the proper lifetime. From these results we see that heavy quark masses reaching $m_Q = 600 \text{ GeV}/c^2$ can be excluded at 95% C.L. for lifetimes longer than $2 \cdot 10^{-9} \text{ s}$. The transition between the two extrema of being fully efficient and losing all decays happens within two orders of magnitudes of the lifetime between 10^{-9} s and 10^{-7} s .

Lifetime	$2 \cdot 10^{-9} \text{ s}$	10^{-8} s	10^{-7} s
$m = 300 \text{ GeV}/c^2$	90%	47%	7%
$m = 500 \text{ GeV}/c^2$	94%	53%	8%
$m = 700 \text{ GeV}/c^2$	96%	58%	10%
$m = 1000 \text{ GeV}/c^2$	98%	64%	11%

TABLE VIII. Fraction of rejected decays of heavy quarks within the geometrical acceptance of the CMS tracking detector. Decays within the tracker are rejected because the particle's trajectory does not reach the outermost tracker layers.

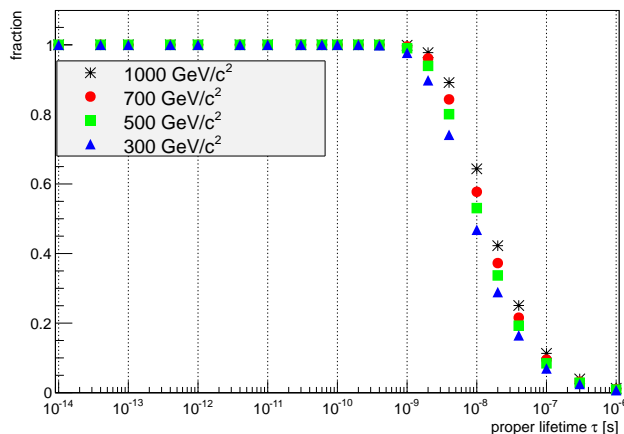


FIG. 8. Fraction of rejected decays of heavy quarks within the volume of the CMS tracking detector as a function of the proper lifetime τ .

4. Discussion and alternative search topologies

We saw from the previous sections that direct searches for prompt decays, which exclude masses up to $m_Q = 600 \text{ GeV}/c^2$, are valid for lifetimes shorter than 10^{-10} s .

On the other hand, searches for HSCP can access lifetimes larger than $2 \cdot 10^{-9} \text{ s}$ for the same mass region. This means that the small window in between these two extrema, corresponding to the region (iii) discussed in Section II C, cannot be excluded yet. In principle, this invisible region could be probed by displaced vertices analyses, but the published analyses appear to not be sensitive enough yet for the heavy quark case. As mentioned in Section III B 2, displacements beyond 50 cm cannot be detected so that these searches are not able to cover the full tracker volume.

To understand the potential of combining all three methods, namely, prompt searches, displaced vertices and HSCP searches, we repeat the simulation from above and calculate the fraction of decays that occur in the invisible region. This is the region with displacements larger than 50 cm, but decaying within the tracker volume. The result is shown in Figure 9. We see that in the worst case scenario, 50% of the decays are lost in these analyses for a lifetime of $\tau = 3 \cdot 10^{-9} \text{ s}$. This represents a moderate decrease of the selection efficiency for a narrow window, so that we can expect a full coverage of the lifetime spectrum in the future.

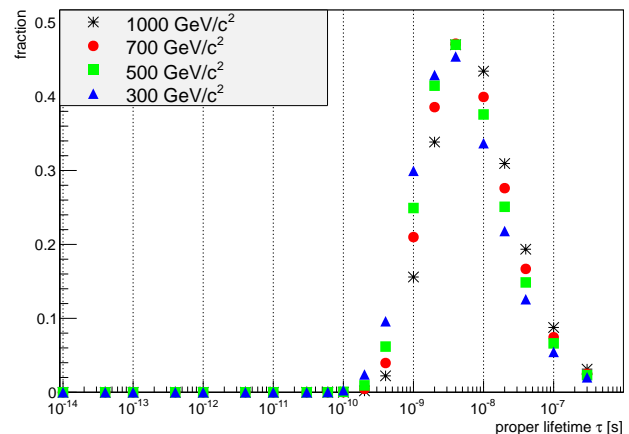


FIG. 9. Fraction of decays of heavy quarks between the acceptance of the displaced vertex analysis and HSCP analyses.

To conclude, we now discuss some of the assumptions made in this section, and their possible limitations. In particular, we considered a general framework in which the new heavy quarks were pair-produced, with kinematics independent of the lifetime of the particle. Our motivation was that the current searches for long-lived R-hadrons formed from stable stops generally assume that strong pair production dominates. In supersymmetric models, however, the situation changes drastically when

the squark masses become large. As pointed out in [62], the gluon fusion mechanism gets suppressed compared to the squark-squark and squark-antisquark pair production processes for large masses due to the decreasing probability for the gluons to carry large fractions of the proton momentum. For scenarios where either the squark masses or the mass of the gluino propagator becomes close to 1 TeV, Higgs and squark weak production start to dominate. The production channels then become more and more model-dependent for increasing masses, arguing for dedicated MC simulations above the TeV scale. Because of the lower production cross-section, models involving such new heavy quarks could be very challenging to detect at the LHC, depending on how well the signal signatures can be discriminated.

Another important limitation that concerns the future HSCP searches for even higher masses is the required timing to detect such slowly moving particles. While the LHC design bunch spacing is 25 ns, the 2011 and 2012 LHC runs have been using a bunch spacing of 50 ns. A recorded event has to be contained in a single bunch, even tighter constraints may be imposed by the readout of the tracking devices. To be visible in HSCP searches, a particle must traverse the full tracker and muon systems in order to trigger the event. Therefore, this is required to happen within a time frame of $O(10^{-8} \text{ s})$.

As discussed in the previous sections and visible in Figure 6 the average velocity reduces with the mass. Since particles with a mass $m_Q = 1000 \text{ GeV}/c^2$ have an average velocity of $0.6c$, this means that they propagate a distance of 3 meters on average within 10^{-8} s , just enough to pass through the tracker volumes.

This estimation shows that the HSCP searches have an intrinsic limitation as the excluded masses increase beyond the TeV scale. Stable quarks with larger masses might evade the current searches as such slow states cannot be detected. There are not many options to overcome this problem. One possibility for mitigation is the search for short tracks. An event triggered in the muon system by a slowly moving particle may still contain a few tracker hits in the outermost tracker layers. This would require new track reconstruction algorithms searching for hits of highly ionizing particles pointing towards the triggering signature. One can measure the time of flight from the outermost tracker layers to the triggering muon stations which should be large and facilitates background suppression.

In case the heavy quark decays within the tracker volume, the signature to be searched for may be one or more displaced jets, which trigger the event, and originate from the heavy quark decay. In addition a short track with a few hits and large dE/dx pointing to the decay vertex could be required. This signature may have relatively low backgrounds as the jets should have a large transverse momentum. The tracks within these jets are not required to arise from the primary interaction vertex which makes track reconstruction difficult. To circumvent this, one could perform a regional search for short tracklets

pointing towards the energy deposit in the calorimeter.

Besides the possible differences between the kinematics of long-lived quark scenarios, a final remark to this discussion concerns their expected production rates. While we assumed above that the heavy quark pair production cross-sections were of the same magnitude as the rate of particles hadronising into bound states, we stressed in Section IID that this is not the case in general. As a matter of fact, smaller cross-sections are expected due to the possibly large suppression arising from the quarkonium wave function, which also modifies the associated decay phenomenology. In particular, η_Q production occurs to be smaller by at least one order of magnitude with respect to $Q\bar{Q}$ pair production when accounting for the attractive potential between the two heavy quarks [34]. Precise calculations would be needed to refine our analysis and the above discussion might need to be adjusted in case of strongly bound states.

IV. SUMMARY AND CONCLUSIONS

The current searches for heavy quarks at the LHC mostly ignore the option of long lifetimes. Although a new chiral family of fermions is now strongly disfavoured from the recent Higgs search results, such a scenario remains of prime importance when considering vector-like quarks beyond the Standard Model. As non-chiral fermions decouple in the limit of vanishing mixing with the lighter generations, they can be long-lived and form bound states. Dedicated searches for novel heavy $Q\bar{Q}$ quarkonia, Qqq baryons and $Q\bar{q}$ ($\bar{Q}q$) open-flavour mesons might provide promising strategies for future investigations.

As we have seen, searches for prompt decays are still valid for long lifetimes to a certain extent, but the assumptions about branching ratios and the potential loss of efficiency need to be considered. We showed that these analyses start to become insensitive for lifetimes longer than 10^{-10} s , corresponding to $Q-q$ quark couplings below the 10^{-9} level. For lifetimes beyond 10^{-10} s , searches for displaced vertices in the tracker volume may play an important role. Still, the published analyses appear to not be sensitive to long-lived heavy quarks, either due to the selection criteria that reject them or due to a lack of statistics. We proposed some improvements to these analyses to extend their reach to long-lived heavy quarks as well.

Moreover, our reinterpretation of the HSCP searches indicates that quark masses of $600 \text{ GeV}/c^2$ can be excluded at 95% CL for lifetimes longer than $2 \cdot 10^{-9} \text{ s}$. This result however assumes that the interactions of the heavy quarks with the detector material are similar to that of stop particles. As discussed in this review, there are potential restrictions to such an assumption, and the forthcoming searches should be interpreted in a model-specific context. Additionally, it is usually considered that the bound states production cross-sections are com-

parable to that of pair-produced heavy quarks. This is not necessarily the case for the reasons we discussed.

For long-lived particles above the TeV scale, further limitations include the fact that slowly moving particles do not fit into the nanosecond time frame required to read out the detector within one LHC bunch crossing. We suggested extensions to the existing searches, such as to include short tracks or alternative topologies to extend their reach to extremely high masses.

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